A Study of Mine Blasts and Rockbursts in the Pacific Northwest

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Abstract

We have collected regional broad-band and densely-spaced short-period data for nearly 40 mining explosions from the Centralia mine, from two rockbursts in northern Idaho, and from several other explosions in the Columbia River Basalt and elsewhere in Washington state. These recordings, for events with magnitude 2.5 or larger, are being analyzed to determine the characteristics of the seismic signals that identify these events as explosions or rockbursts.

The type of delayed blasting at the Centralia mine may not be conducive to the detection of spectral scalloping or nulling, and this effect has not been clearly observed in preliminary spectral analyses of the regional seismic signals. However, these and other blasts generate relatively high-amplitude Rayleigh waves (Rg) that allow their identification as explosions at close distances. We are planning to make near-field deployments using broad-band, high-frequency seismic systems to characterize the effect of the delay pattern and charge sizes on the generation of regional seismic phases from the explosions at Centralia.

Rockbursts from the northern Idaho region are due to implosional and fault-slip mechanisms, as determined from in-mine seismic systems. Such events are often triggered by the failure of pillars, in some cases during de-stressing operations. Such events may be of particular interest to discrimination researchers.

We are preparing to arrange for the recording of Centralia coal mine blasts on a USGS refraction line in September. Several hundred portable recorders will be operated along a 400 km profile that passes within 20 km of the Centralia mine. This will provide a comparison of the delay-fired mine blasts to the single-shot USGS explosions.

We are currently in the process of integrating the broad-band stations of the USGS National Seismic System, the Canadian Digital Seismic Network, and the broad-band elements of the Pacific Northwest Seismograph Network, and Pacific Northwest Laboratory's own broad-band recordings into the data base.We have established cooperative relationships with other regional seismic arrays and mine operators to exchange data on the mining explosions and the Idaho rockbursts. In the future, we will compare these mine seismic signals with recordings of shallow earthquakes located in the same regions as the mines.

Key words: chemical explosions, discrimination, mining, rockbursts, seismic sources.

Objective

The objective of the field study is to collect and characterize the seismic signals from large mine and quarry blasts, mining-induced earthquakes or rockbursts, and shallow earthquakes. These signals will be used to test regional seismic discrimination methods, utilizing a combination of pre-existing, permanent short-period and broad-band seismic networks, and near-source recordings made with portable, broad-band, high-frequency systems.

The focus of the field study is the Pacific Northwest (Washington, Oregon, Idaho, and southern British Columbia, Canada) in areas of active mining and industrial blasting. Of particular interest are blasts registering greater than magnitude 2.5. These blasts are routinely recorded, located, and identified as blasts using the data from a regional seismographic network throughout Washington and Oregon. In addition to mine blasting, seismic events induced by deep mining activities in northern Idaho occasionally exceed magnitude 2.5 as determined on regional seismic networks in Washington, northern Idaho, and western Montana.

In some areas, mining explosions have a characteristic frequency-amplitude distribution that reflects the shot pattern. A pattern of constructive and destructive interference between the shot holes can sometimes generate a frequency spectrum with a "scalloped" appearance, with spectral nulls resulting from the destructive interference at an evenly-spaced set of frequencies (Baumgardt and Ziegler, 1988; Hedlin et al., 1990, Smith, 1989). However, this is not clearly evident in the seismic signals recorded on the regional networks, possibly because they can only be observed at short distances, or alternatively because the pattern of delayed detonations is not systematic enough to create the interference pattern.

Preliminary Research Results

Figure 1 shows the locations of short-period stations that comprise the Pacific Northwest Seismograph Network (PNSN). The regional seismic networks are comprised of short-period (1 Hz) seismometers, only a few of which record three-component motion, which generally record ground motions in the frequency range of 1-30 Hz. Figure 1 also shows the locations of broad-band stations that have been operated in the region in recent years. We examined the PNSN catalog of explosions to identify the primary areas in which explosions have been located. Figure 2 shows the locations of explosions that occurred in 1994 and 1995, and Figure 3 shows the locations of earthquakes with depth less than 5 km for the same time period.

Centralia Coal Mine. The predominant site of large explosions is currently and has for many years been a large coal mining operation at Centralia, Washington. At the Centralia mine, daily blasting routinely generates seismic events with magnitudes in excess of 2.5. Up to 600 ft. of overburden (a relatively soft sandstone) is removed during the mining at Centralia to expose the main coal seam, which is 60 ft. thick. Cast blasting is not employed at the Centralia mine (cast blasting throws or casts the overburden off of the underlying layers); the overburden is simply broken up with explosives and removed using a drag line. The coal bed itself is not usually shot. Shot holes are 9 in. diameter and are drilled vertically to a depth of approximately 60 ft. A slurry blend of ANFO explosive is usually pumped into the holes, although bags of ANFO are sometimes used in wet conditions. The top 15 ft. are filled with stemming material, and each

hole contains approximately 1000 lbs. of ANFO. Holes are drilled with a 25 ft. spacing, generally 5 to 6 rows and 10 to 40 holes/row in a rectangular pattern. The largest explosions at the mine occasionally include as much as 260,000 total pounds of explosive.

The explosions are delay fired using non-electric, or "pyrotechnic", delay systems. The delay pattern consists of a 25 ms (millisecond) delay along the spacing of each row (parallel to the free face), and a row-to-row (or "burden") delay of 84 ms. The spacing and burden delays are arranged across the surface of the area to be blasted, and an additional 500 ms down-hole delay is located at the bottom of each shot hole. In this way, each of the shots has been first delayed from hole-to-hole and row-to-row by the surface delays, and is then additionally delayed by the larger 500 ms down-hole delay. The spacing, row (burden), and down-hole delays are provided by devices manufactured in a variety of preset time lengths. Measurements made at the Centralia mine indicate that for the 500 ms delay mechanisms, there is a total variation of plus or minus 3.5 ms, and that this 1.5% variation is expected to also affect the 25 ms and 84 ms delays at the surface.

The Centralia mine staff are currently in the process of providing detailed maps of a selection of blasts recorded by the regional seismic network. These maps and descriptions provide exact locations of at least 4 of the shot holes (generally the corners) and the delay pattern that was used and the amount of explosive in each hole.

There have been 37 explosions at the Centralia mine in 1995 that exceeded magnitude 2.5, and 13 of these equaled or exceeded magnitude 3. We have assembled waveform data for all blasts larger than 2.5 in 1994 and 1995, including recordings by four broadband stations in the region. Seismic signals from a set of 20 explosions in 1994 are shown for a nearby seismic station (LMW, approximately 30 km east of the mine) in Figure 4. Most of these explosions can be easily identified as explosions because of the large Rayleigh wave (Rg) they generate (e.g., Kafka, 1990), but the amplitude of the Rayleigh wave is highly variable. We hope to correlate the relative phase amplitudes and spectral characteristics of these blasts with the detailed information from the mine operators.

Black Diamond Mine. The only other coal mine in Washington is located near Black Diamond but the explosions at this mine have all been less than magnitude 2. At the Black Diamond mine, the shot geometry consists of 35 ft. deep holes, stemmed for the top 12 ft., with the holes spaced 15-16 ft. in both directions. There are generally 4-5 rows consisting of 8-10, 6 in. diameter holes. The delay pattern for these shot is 17 ms along the spacing of each row, and 42 ms between rows. Two down-hole delays are often used here with one placed near the bottom of the hole (175 ms), and a second placed near the mid-depth of the hole (200 ms). Each hole has from 200-300 lbs. of ANFO, and the total amount of explosives detonated during the shot infrequently exceeds 10,000 lbs.

Figure 5 shows the total amount of explosives used in each shot at the Black Diamond mine from August 1994 to June 1995, plotted versus the magnitude determined from the seismic array. Many of these shots were too small to trigger the seismic network recording, and these are shown as a magnitude of zero. The seismic network triggers on most of the larger charges, and progressively misses a greater number of smaller ones, as indicated by the increasing density of "magnitude 0" points at small charge sizes on this plot.

Other blasting areas. Large open-pit copper mines in southern British Columbia near Penticton (see Figure 2) blast an average of 200 times per year with typical blasts ranging from 25,000 lbs. to 270,000 lbs. of explosives per blast. All four mines blast use delayed shots, both down-hole and on the surface. Highland Valley Copper in Logan, B. C. consistently has the largest blasts, with mine personnel manufacturing and loading the bulk emulsion on site. We have also contacted the largest coal mines in southeastern British Columbia and southwestern Alberta to determine if their blasting activity might be of a sufficient scale to be of interest.

The most difficult type of explosion to identify is the occasional blast to obtain rock for road or railroad grade material, although these blasts seldom exceed magnitude 2.5. Many of these explosions are detected in the Columbia River Basalt of southeastern Washington, and the mining operation for railroad ballast near Connell (see Figure 2) has agreed to provide us with information on their blasting practices.

Northern Idaho Rockbursts. The northern Idaho silver mining district lies just to the east of the PNSN, and seismic events induced by the mine frequently exceed magnitude 2.5 and are recorded by the regional array. In addition to the PNSN, there are seismic arrays in northern Idaho and western Montana that also record events in this region. Figure 6 shows the location of seismic events in the region of the four rockburst-prone mines from 1983-1992 that have been derived from the catalogs from these regional seismic arrays. The precision of these event locations is relatively poor, on the order of 20 km, but it is clear that there is a concentration of seismic activity near the mines, although naturally occurring earthquakes also occur in the region. We have undertaken an effort to gather information from the mine operators and the U.S. Bureau of Mines, Spokane Research Office (USBM) on the characteristics of these mine-induced events, and to unambiguously separate actual rockbursts from natural background seismicity.

Several of these mines operate in-mine seismic systems that are used by the mine operators to detect and locate rockbursts. Two of these mines also operate a "macro-seismic", or "mine-wide" system provided by the USBM. These systems include 10-12 geophones or accelerometers in remote areas throughout the mined region. The spacing of these sensors can be as large as a few km, and the geometry is designed to provide three-dimensional coverage of events in the mine for focal mechanism studies by the USBM. The mine monitoring systems and the rockburst characteristics are described in a series of papers published by the USBM (Maleki, 1995)

The Lucky Friday mine has had a long history of rockbursts. In the early 1980's, rockbursts were often caused by the failure of pillars left between mined out areas. There are several instances when attempts to de-stress the remnant pillars resulted in rockbursts as large as magnitude 3. The largest event to occur since 1989 was a magnitude 4.1 event on August 16, 1994. This event caused 2 in. of closure in a mined-out area approximately 500 by 500 ft. at the deepest level of the mine, 5570 ft. below the surface. Recently, a magnitude 2.9 rockburst occurred on June 23, 1995. At the Lucky Friday mine, the larger rockbursts are not correlated with mining activities, although smaller events are correlated with the rate of material extraction, and events such as the pillar collapses during de-stressing or removal are clearly induced by mine activity.

Focal mechanism studies indicate that many of the smaller rockbursts and some of the larger

ones have an implosional mechanism. The larger events usually have a significant fault-slip component that would make the events more earthquake-like. We obtained a short list of the largest rockbursts in 1994 and 1995 from the mine, and later received a more extensive list from the staff of the USBM. We have begun collecting seismograms from the PNSN and other regional arrays in northern Idaho and western Montana, and also from broadband stations in the region (see Figure 1) for these events.

Examples of the waveforms collected from the August 16, 1994, magnitude 4.1 rockburst at the Lucky Friday mine are shown in Figure 7 for a selection of stations that form two profiles, one directed southwest from the mine through eastern Washington and into central Oregon, and another directed more westward across the Cascade mountains and into Puget Sound. There appears to be greater attenuation of the signals on the latter profile, possibly indicating topographic or geologic blockage of the waves (the distance range for both profiles is 100-600 km from the mine).

Recommendations and Future Plans

The second phase of the field study involves actively collecting three-component broad-band signals near the most significant blasting activities identified. We will deploy Guralp CMG-40T seismometers with REFTEK portable digital recorders at a variety of azimuths and ranges from the Centralia mine, to search for spectral modulation from the delay firing, and to characterize the generation of the Rayleigh waves that identify the shallow depth of explosions.

In September, 1995, the U.S. Geological Survey will be recording a series of 17 controlled explosions along a seismic refraction line from the Pacific coast to eastern Washington. This line will be occupied by approximately 250 USGS REFTEK seismic recording instruments and an additional 500 instruments of other types. The line passes 20 km to the south of the Centralia mine, as shown in Figure 8, and this provides an opportunity to further examine the evolution of the Rayleigh waves generated at the mine, and an opportunity to compare the delay-fired mining explosions with the simultaneously-fired USGS explosions. We are making arrangements to schedule the recorders to record one or two of the Centralia mine blasts.

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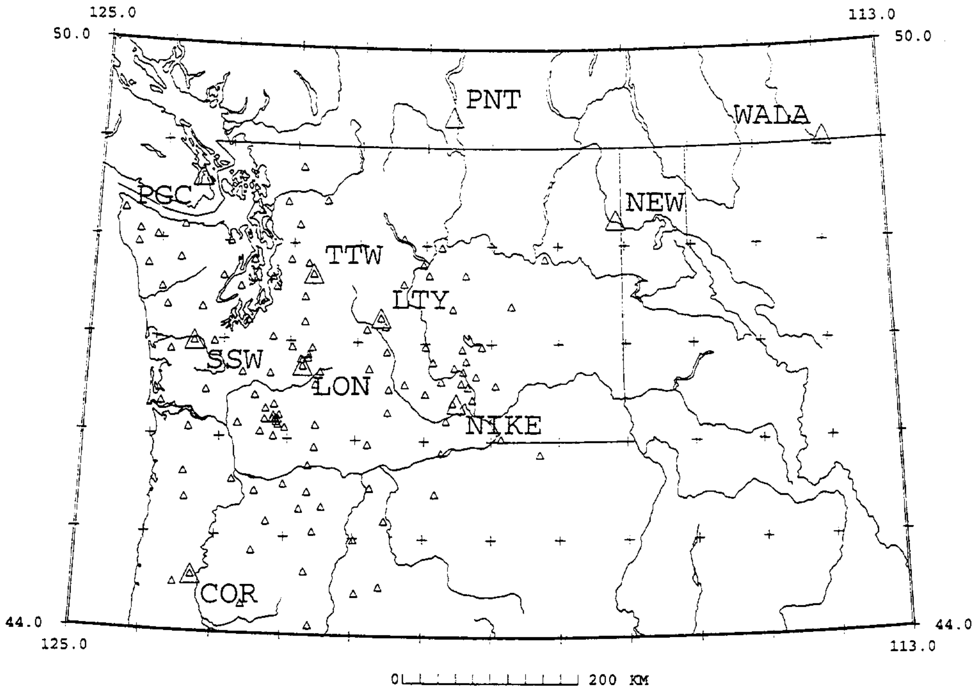

Figure 1. Location map of the Pacific Northwest Seismograph Network (small triangles), and regional broad-band seismic stations (large triangles with station names).

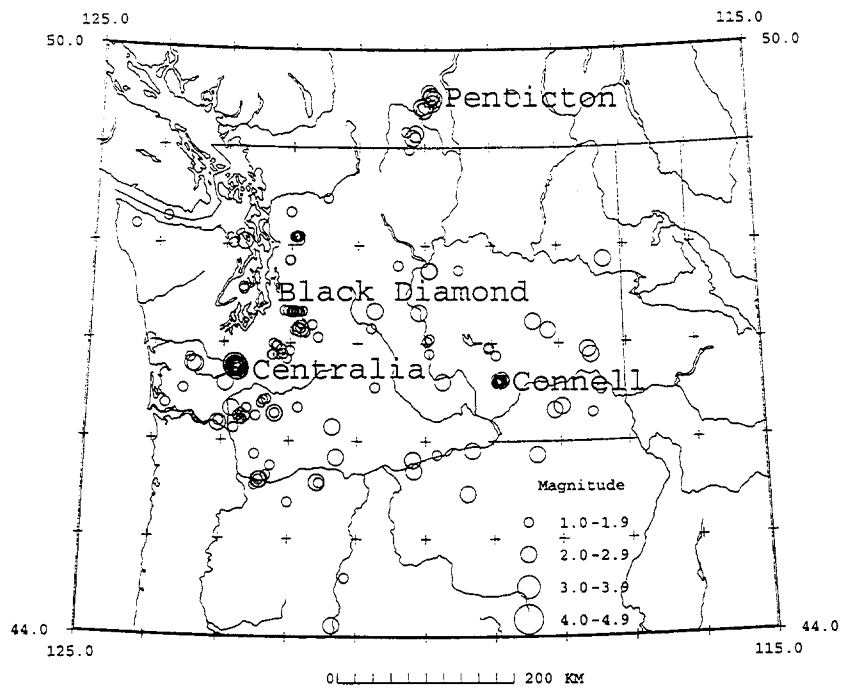

Figure 2. Location map of explosions 1994-1995 with coda-duration magnitudes larger than 1.5. Named sites are those we have obtained detailed blasting information from mine operators.

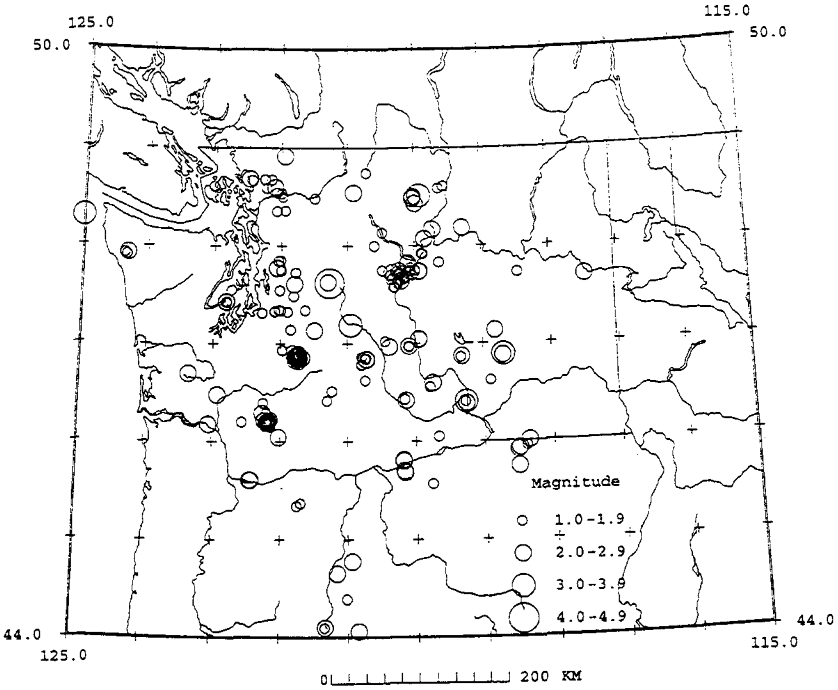

Figure 3. Locations of earthquakes 1994-1995 with coda-duration magnitudes larger than 1.5. Hypocenter depths for these events are less than 5 km.

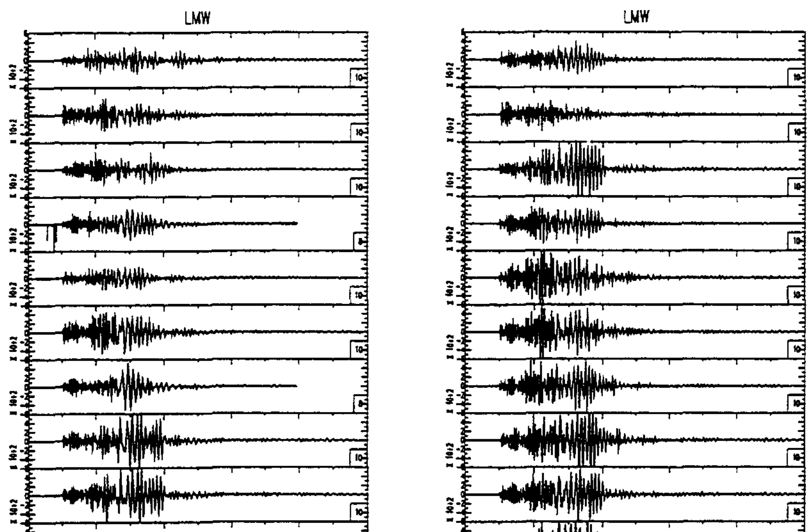

Figure 4. Seismic signals from the Centralia mine recorded at station LMW. The prominent, low-frequency signal on these traces is the Rg phase, indicating a shallow depth event.

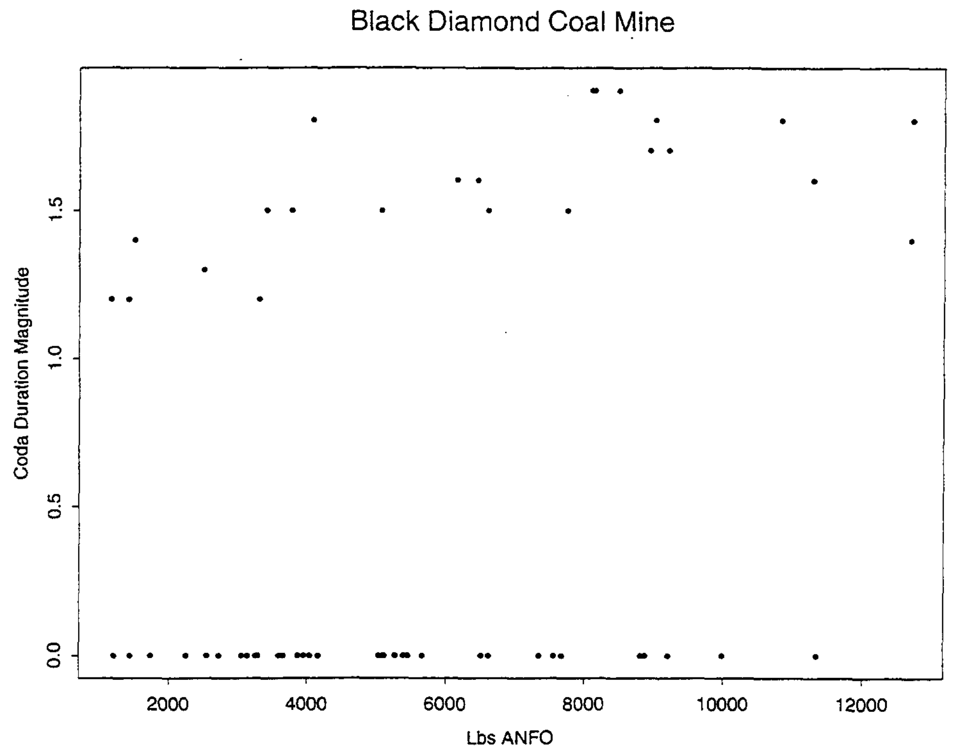

Figure 5. Relationship between total explosives used at the Black Diamond mine and the resultant coda-duration magnitude. Magnitudes of 0 indicate that the event was not located by the network.

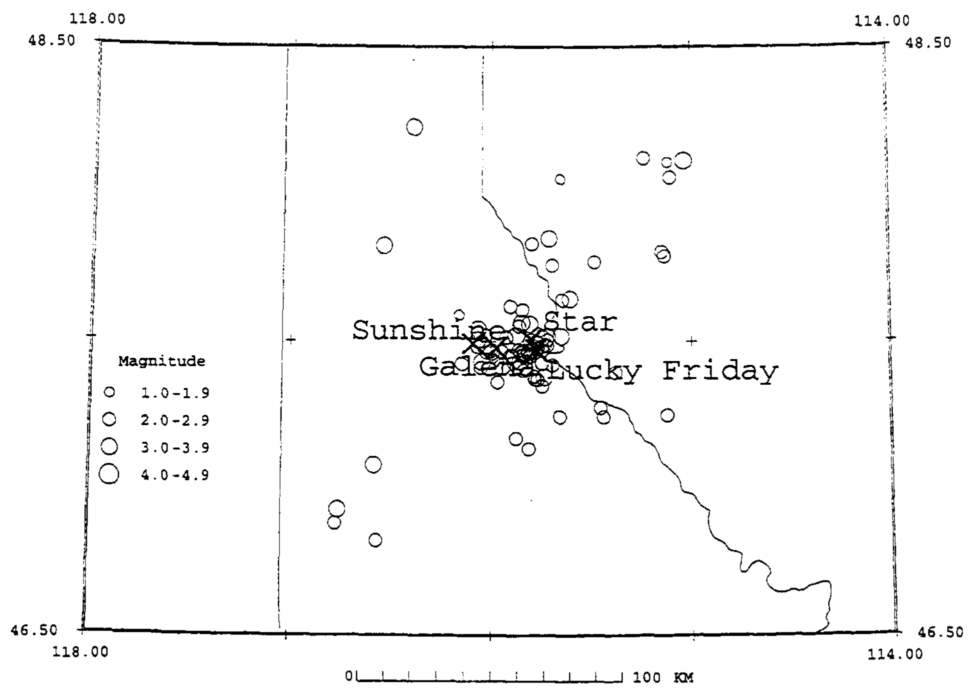

Figure 6. Location map of northern Idaho seismic events, 1983-1992. Most of the events in this region are triggered by the four deep silver mines indicated by the large crosses.

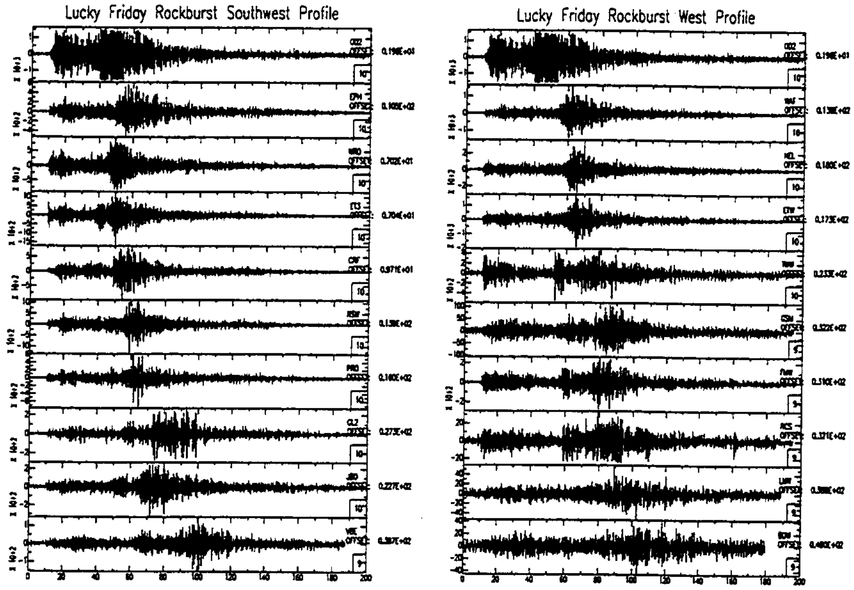

Figure 7. Seismograms from the August 16, 1994 Lucky Friday rockburst recorded from southwestern and western azimuths on the Pacific Northwest Seismograph Network.

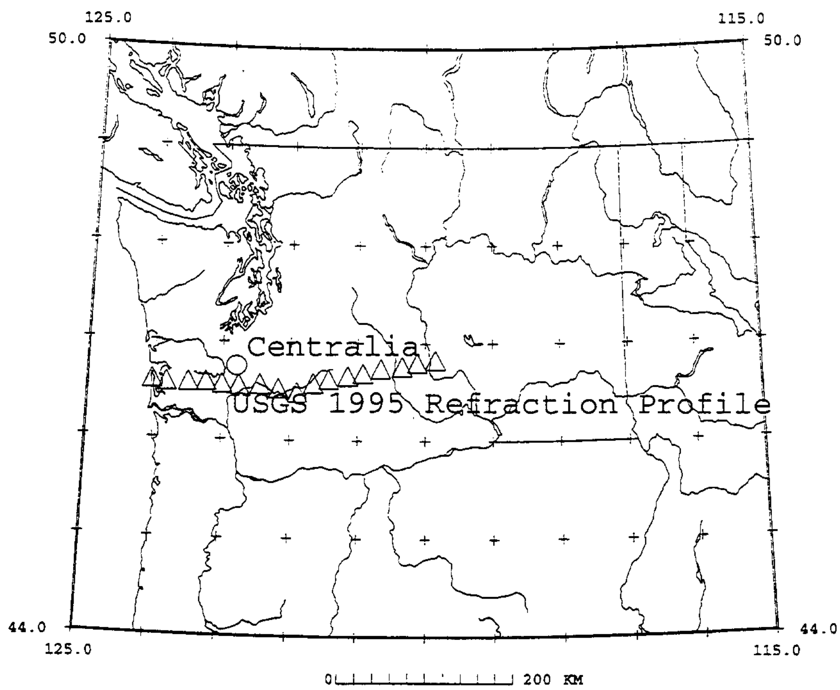

Figure 8. Planned U.S. Geological Survey refraction profile explosions and the location of the Centralia mine. The refraction line will be occupied by several hundred seismic recorders.